Jet Propulsion Laboratory
California Institute of Technology

Modeling the Aerodynamics of Supersonic Parachutes for Mars Applications

MECH 598/698: Aerodynamics
Loyola Marymount University

Clara O'Farrell
Jet Propulsion Laboratory
California Institute of Technology

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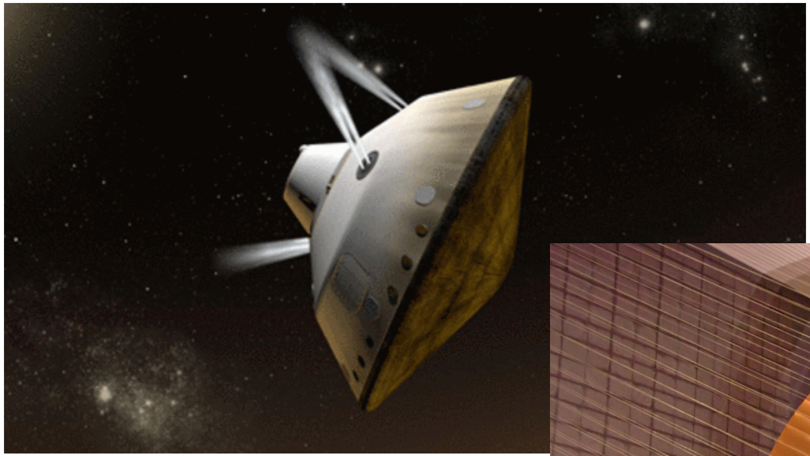
ASPIRE

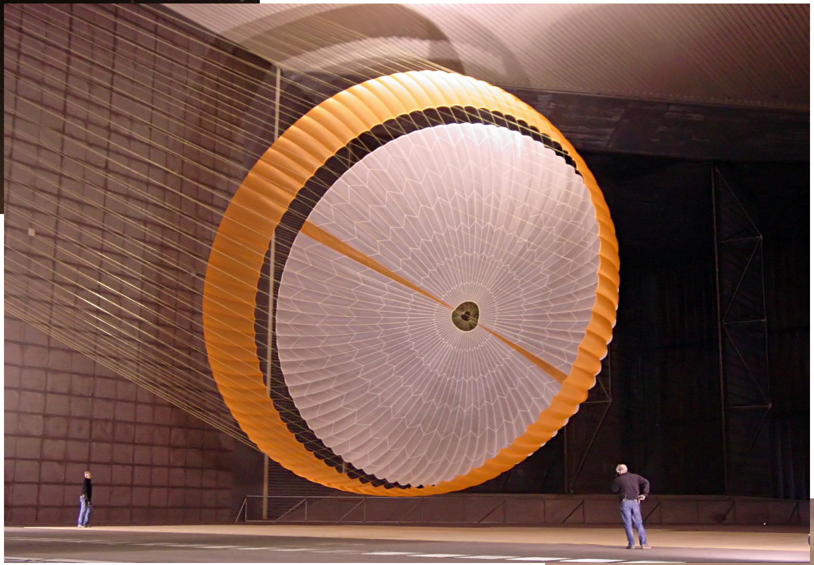
Overview

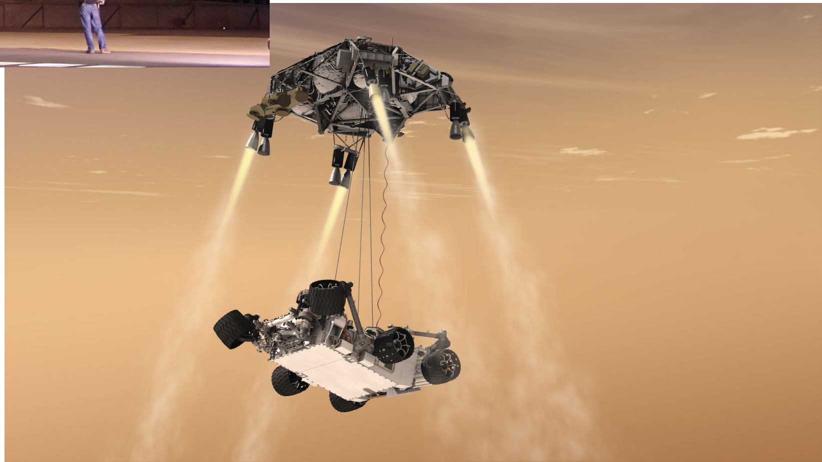
ASPIRE

1. Mars Entry, Descent & Landing and the ASPIRE project
2. Parachute terminology & introduction to parachute aerodynamics
3. Measuring parachute aerodynamic coefficients
4. ASPIRE's supersonic flight tests

Mars Entry, Descent & Landing







Parachutes for Mars EDL

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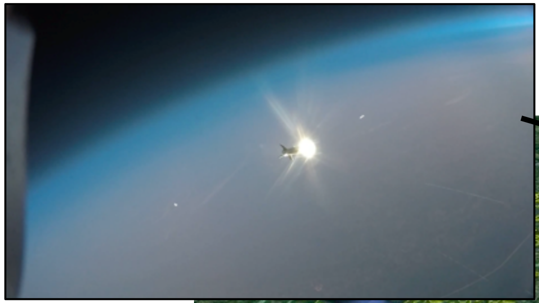
- Parachutes are primarily drag-producing devices and their efficacy is driven by the dynamic pressure

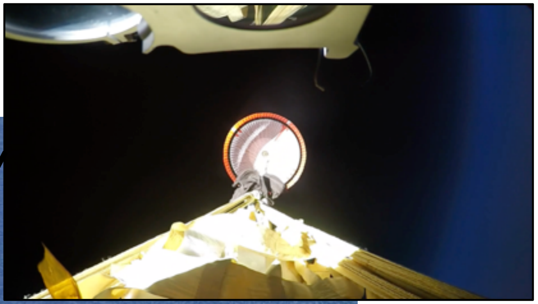
$$\text{Drag} = C_D \tfrac{1}{2} \rho V^2$$

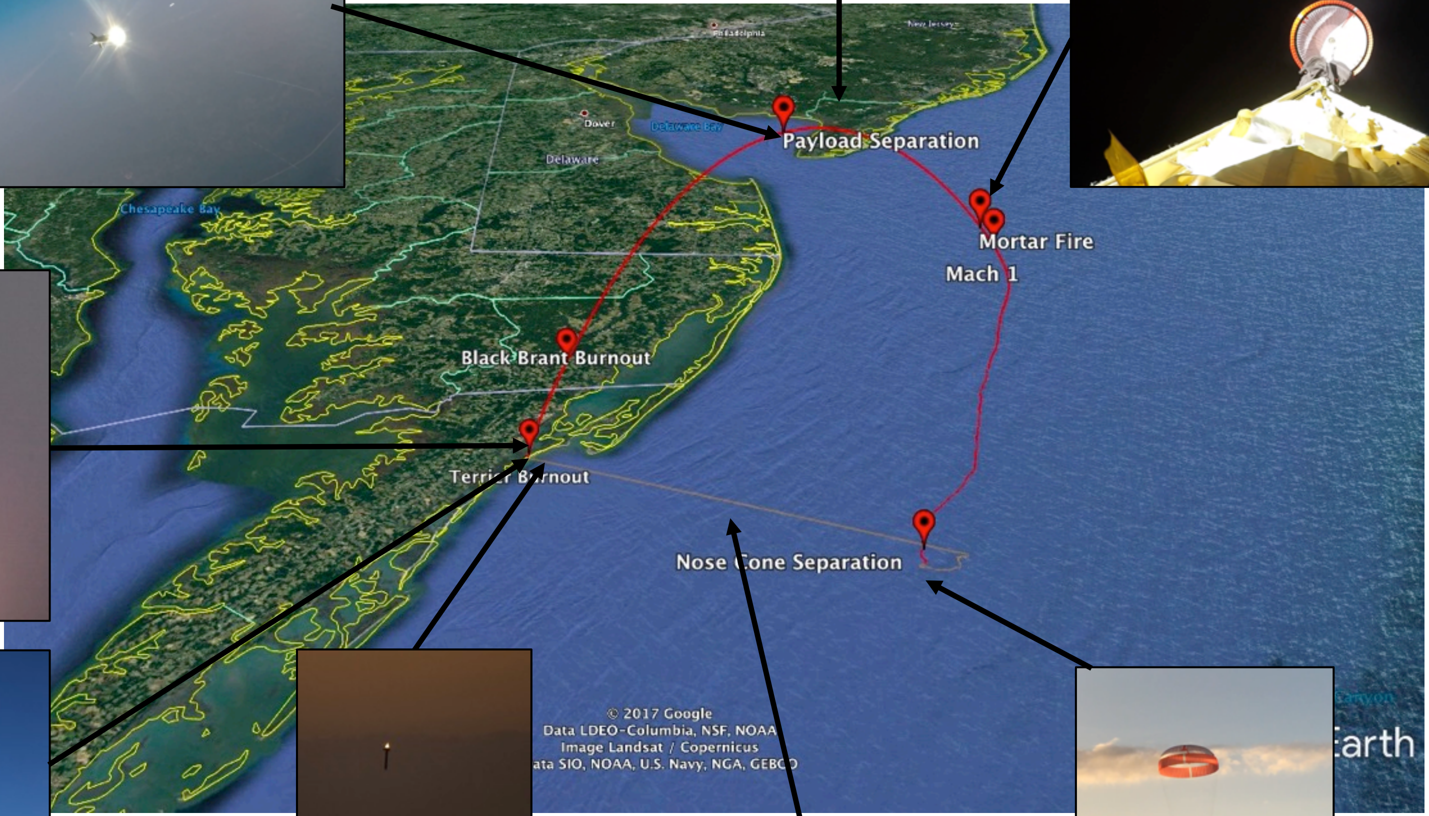
- Atmospheric density at Mars is <1% that on Earth
- Drives the need for large, supersonic parachutes to land robotic payloads on the surface
- Also makes testing full scale parachutes at Mars-relevant conditions challenging
  - Matching dynamic pressure *and* Mach number in ground tests is impossible for full-scale parachute
  - Mars-relevant conditions can be achieved through high-altitude supersonic tests
- The **A**dvanced **S**upersonic **P**arachute **I**nflation **R**esearch **E**xperiments Project (ASPIRE) was established to study the deployment, inflation and performance of two candidate parachutes for the Mars2020 project.

The ASPIRE Project



Apogee
L+119 s (~50 km)

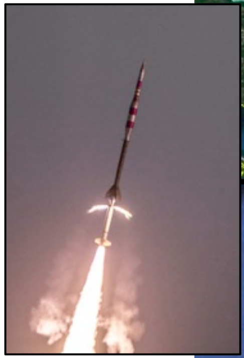




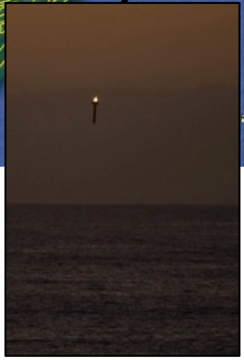
Mortar Fire
L+160-70 s
Alt: 39-45 km
q_∞: 450-850 Pa
Mach: 1.7 to 2

Peak Load
MF +1.5 s
q_∞: 500-1000 Pa
Mach: 1.7 to 2

Nosecone sep.
L + ~26 min
Alt: 3 km

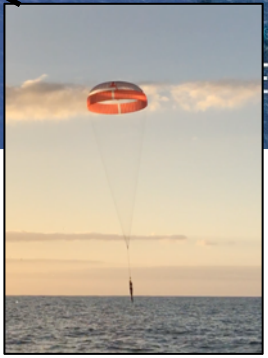


Launch.
Wallops Island, VA



1st stage burnout
L+6.2 s (1 km)

Range
50-100 km



Splashdown
L + ~30 min

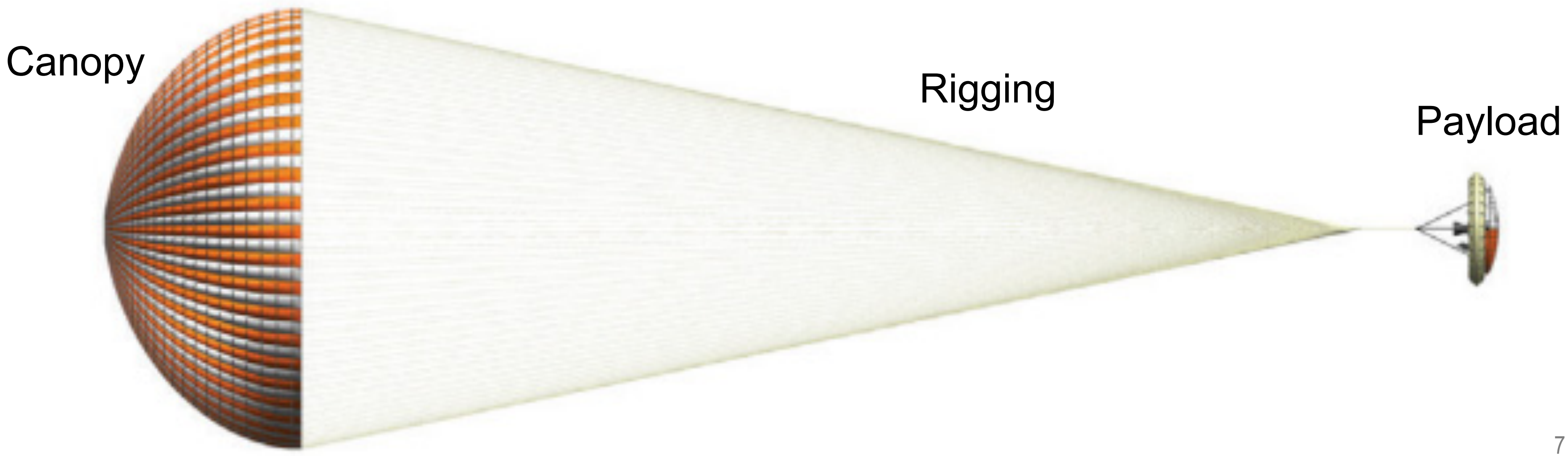
Parachute modeling on ASPIRE

Models of aerodynamics of the parachute system are necessary to:

- Evaluate vehicle trajectory for targeting, range safety, recovery
- Evaluate loads on the parachute
- Evaluate loads & accelerations imposed by the parachute on payload
- Guide sensor selection & placement
- Examine differences between parachutes tested in slender body wakes (test) and blunt body wakes (at Mars flight)

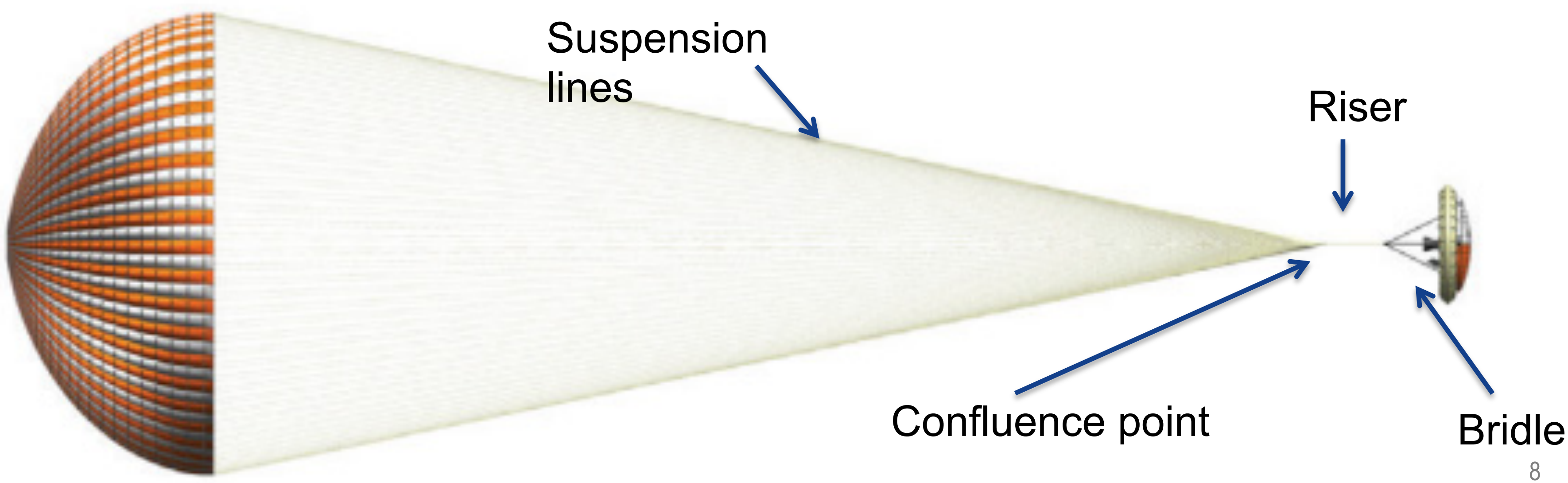
Terminology

- *Canopy*: the main drag-producing area of a parachute system:
  - Open *vent* at the apex
  - *Crown*: area near the apex
  - *Skirt:* outward edge of canopy



Terminology

- *Canopy*: the main drag-producing area of a parachute system:
  - Open *vent* at the apex
  - *Crown*: area near the apex
  - *Skirt:* outward edge of canopy
- *Suspension lines:* load-bearing members extending from canopy to payload
  - Intersect at a *confluence point*
  - May connect directly to payload, or through a *riser*
- *Bridles* allow multi-point attachment to payload

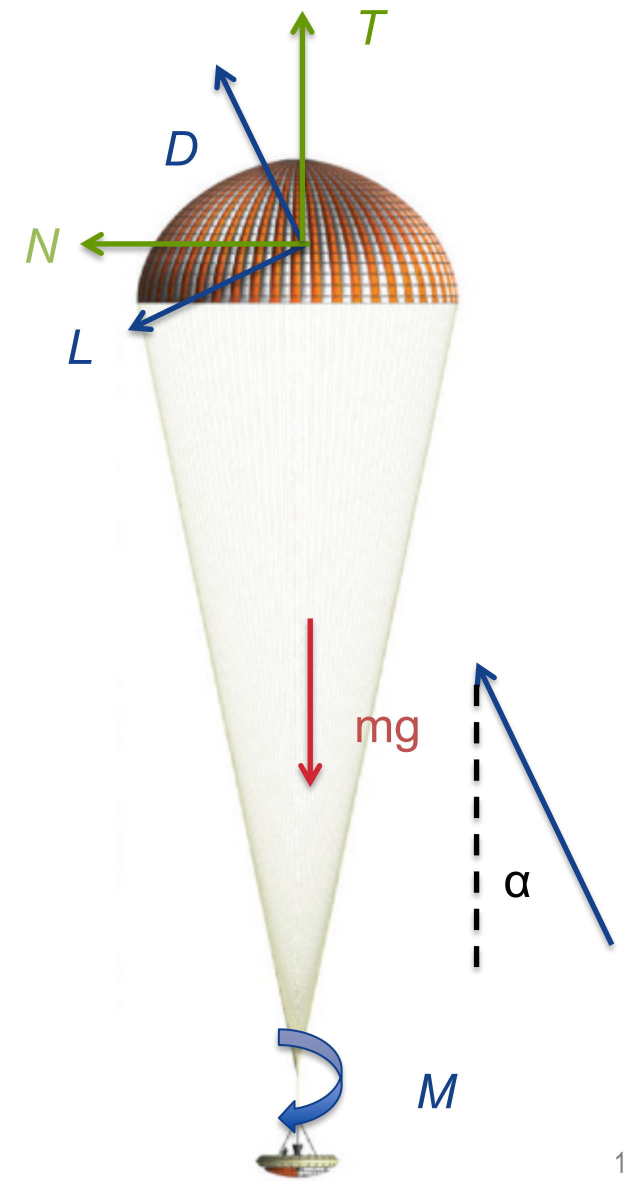


Terminology (cont.)

- *Nominal area* or *reference area* S_0:
  - Total surface area of all of the fabric & gaps in the canopy
- *Nominal diameter* D_0:
  - $S_0 = \pi(D_0/2)^2$
- *Projected area* S_p:
  - Cross-sectional of the inflated canopy
- *Projected diameter:*
  - $S_p = \pi(D_p/2)^2$
- *Geometric porosity*
  - Ratio (in %) of all open areas (eg vent) in the canopy to the nominal area
- *Permeability*
  - Describes the propensity of the canopy fabric to let air flow through its fibers
- *Porosity or total porosity*
  - Term used to describe airflow through the fabric *and* gaps cut into the fabric

Aerodynamics of parachutes

- Axisymmetrical canopy
- Apparent velocity *V*
- Angle of attack measured about canopy axis of symmetry
- Forces on a parachute:
  - Weight of payload and parachute
  - Drag (parallel to *V*)
  - Lift (perpendicular to drag)
  - Tangential force along the parachute axis of symmetry
  - Normal force (perpendicular to *T*)
- Usually express pitching moment *M* about the confluence point



Aerodynamics of parachutes

$$C_L = \frac{L}{1/2\rho V^2 S_0}$$

$$C_D = \frac{D}{1/2\rho V^2 S_0}$$

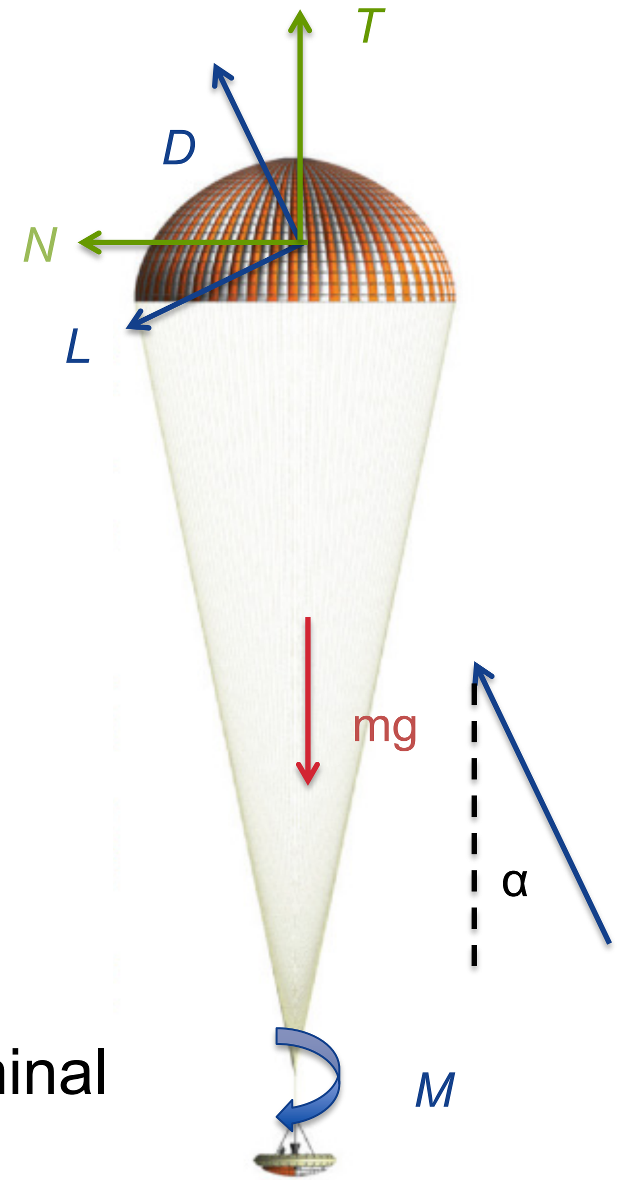
$$C_T = \frac{T}{1/2\rho V^2 S_0}$$

$$C_N = \frac{N}{1/2\rho V^2 S_0}$$

$$C_M = \frac{M}{1/2\rho V^2 S_0 D_0}$$

$$L = N \cos\alpha - T \sin\alpha$$

$$D = N \sin\alpha + T \cos\alpha$$

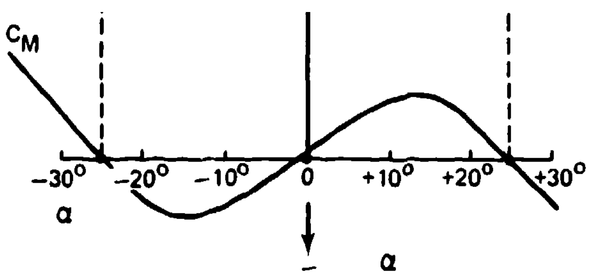


All coefficients are defined wrt the nominal area and diameter

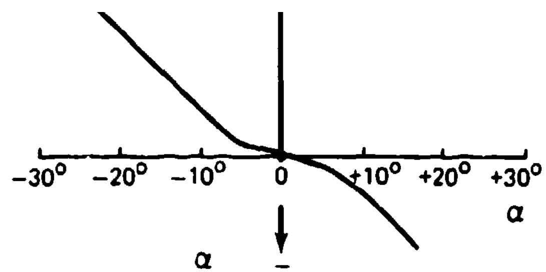
Static stability and C_m

- By convention, a *negative* pitching moment is stabilizing
- For static stability:

$$C_M = 0 \qquad \frac{dC_M}{d\alpha} < 0$$

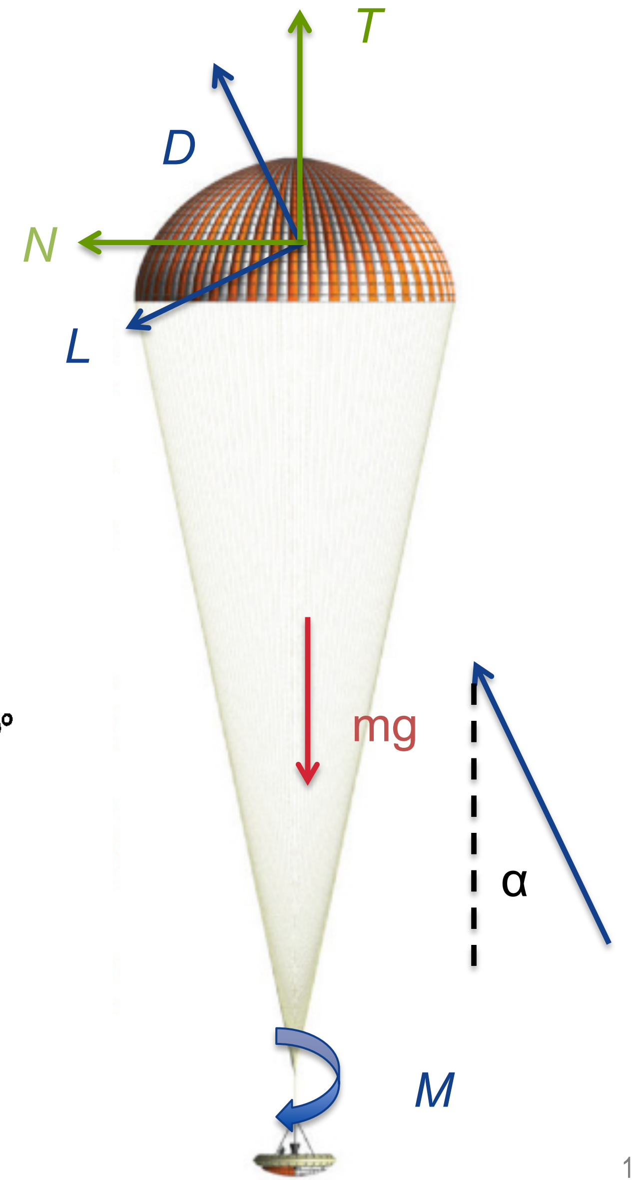


UNSTABLE PARACHUTE



STABLE PARACHUTE

- Use angle of oscillation as measure of stability



Measuring parachute aerodynamic coeff.

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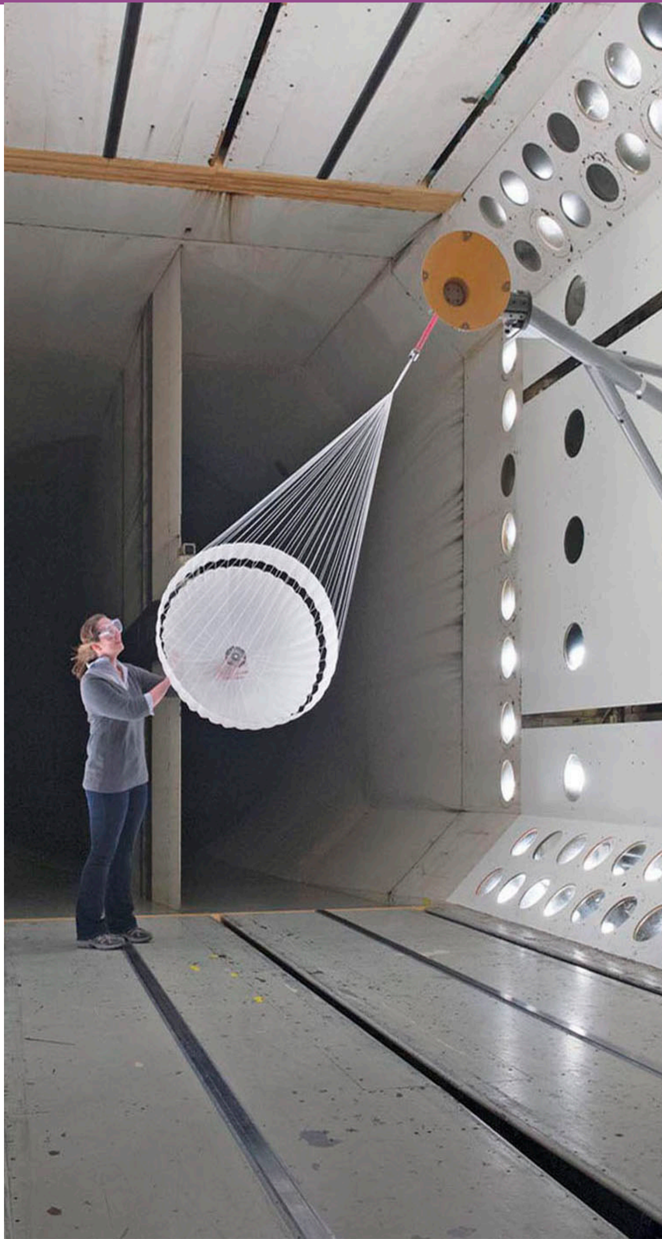
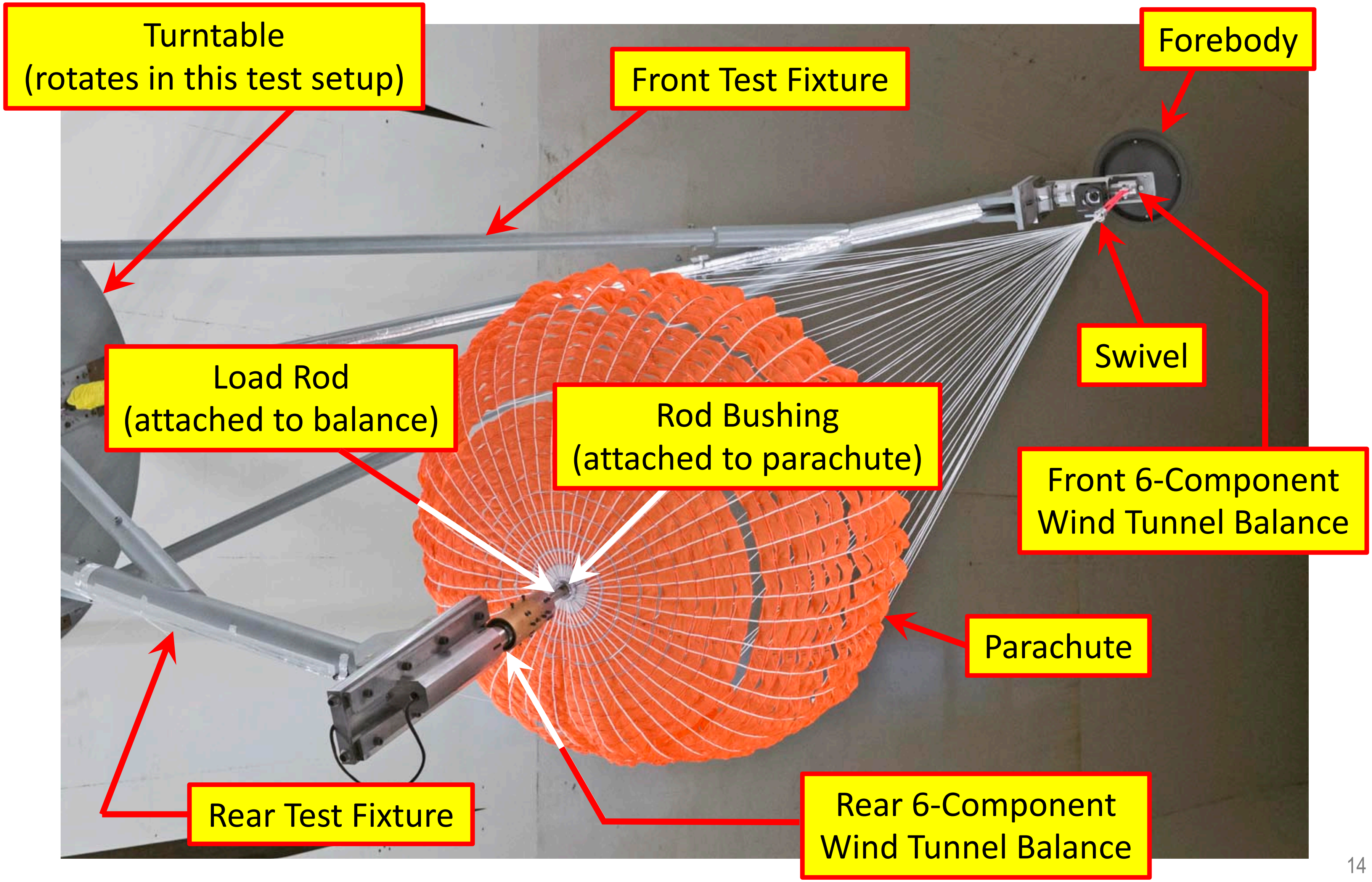
- In 2014, the NASA Engineering & Safety Center (NESC) and JPL conducted a wind tunnel test of scaled parachutes
- Objective: to measure the drag and static aerodynamic coefficients of the model parachutes
- Conducted at the Transonic Dynamics Tunnel (TDT), which can be pumped down to test at low densities (~5% Earth sea level)
- Models were 5% scale of the 21.5 m MSL parachute (~5 ft)
- Atmospheric density also affects the effective fabric permeability, so tests were conducted using two canopy fabrics:
  - PIA-C-44378D Type I, White (“low” permeability)
  - PIA-C-7020D Type I, Orange (“standard” permeability)



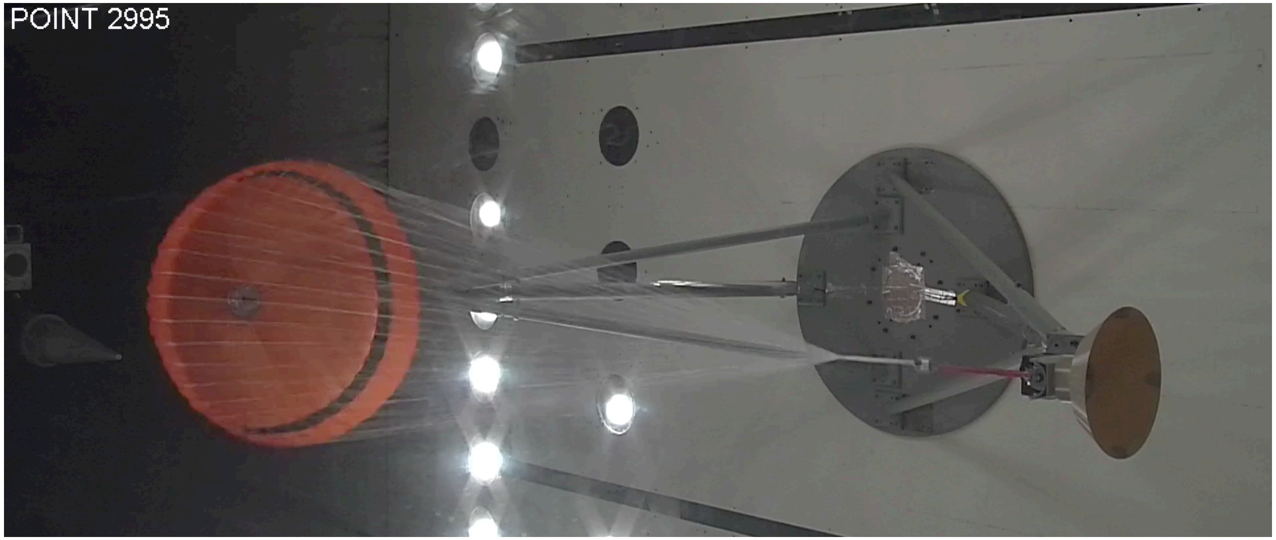
Test setup – static coefficients



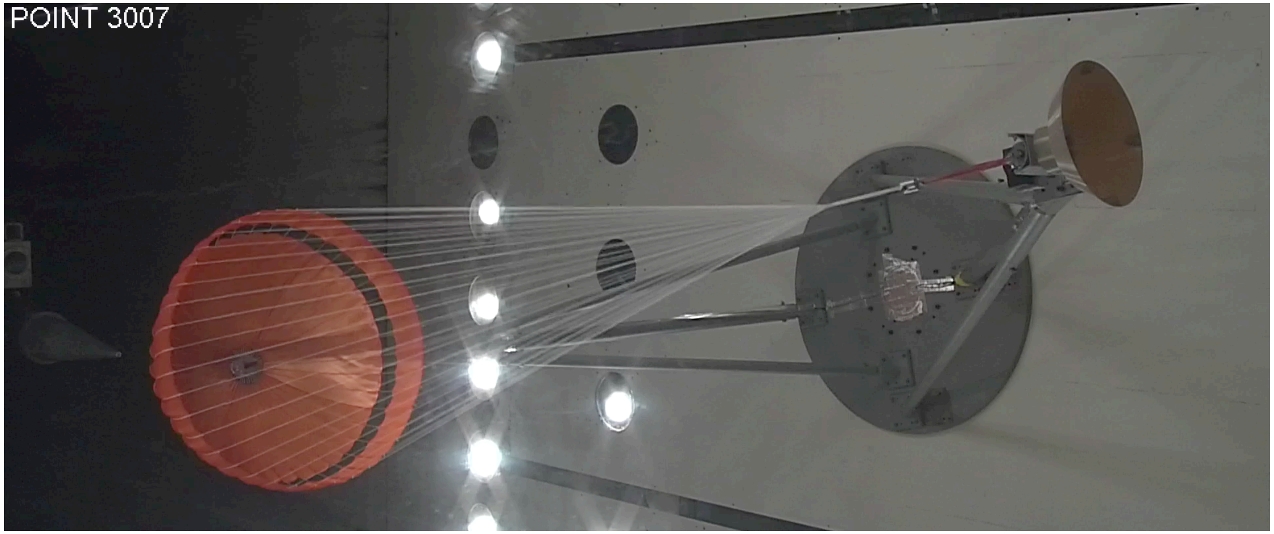
Test setup – static coefficients

DGB Parachute with Orange Fabric (PIA-C-7020D Type I fabric, “standard” permeability)

$\alpha = 0°$

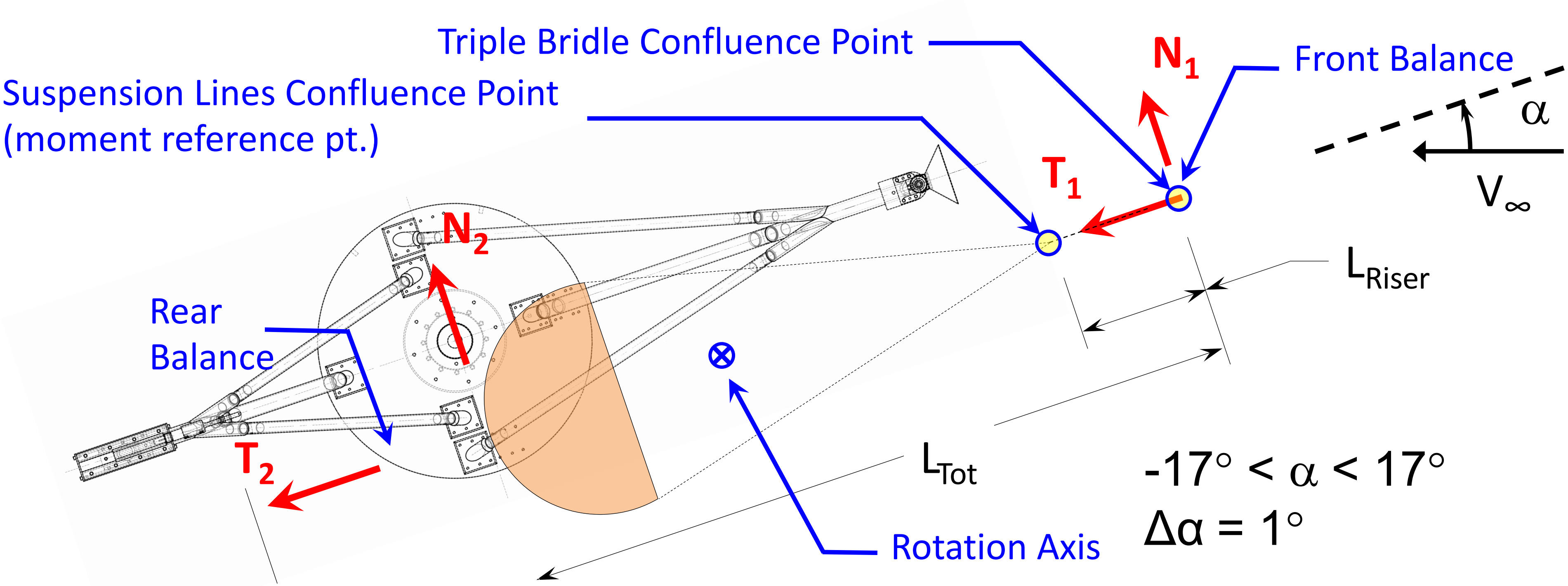


$\alpha = 13°$



Data analyses

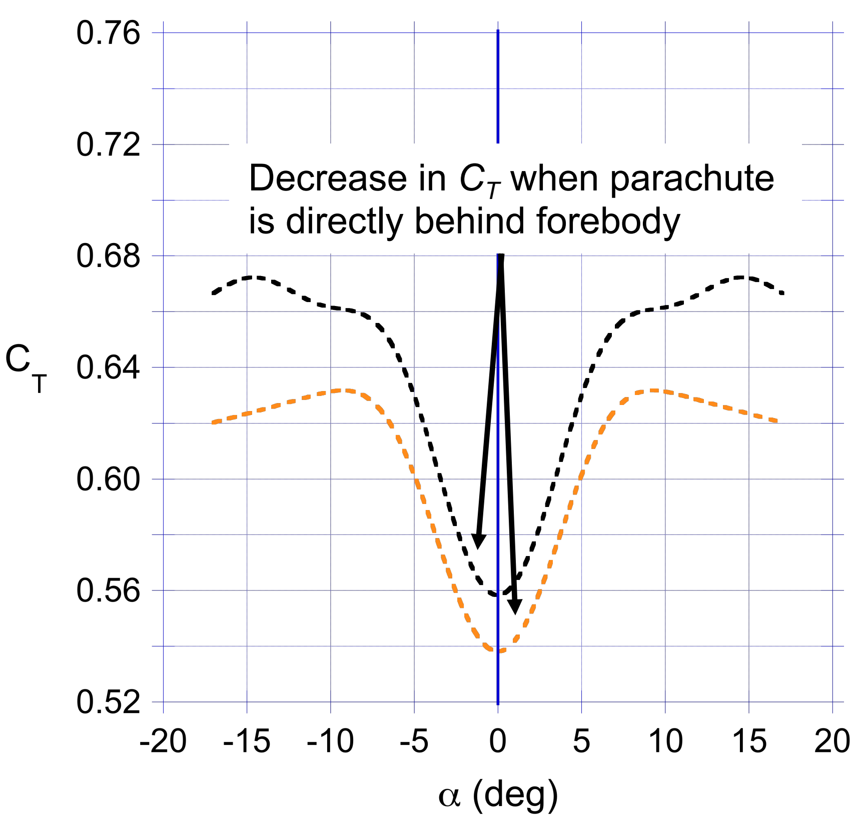
ASPIRE

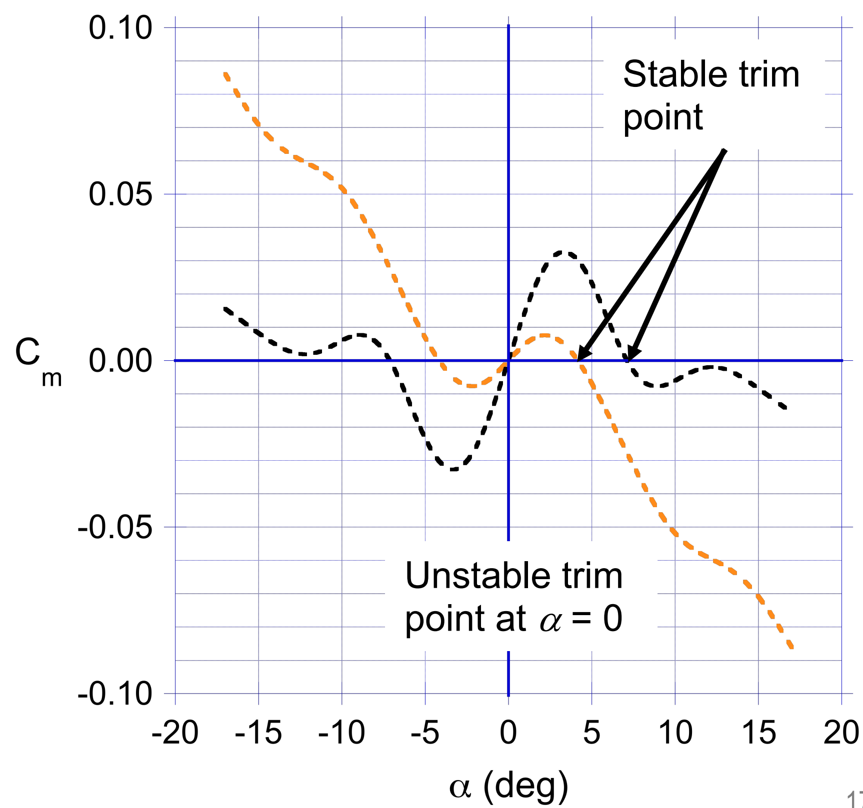


Forces and Moment	**Coefficients**
Tangential Force = T = T_1 + T_2	$C_T = \dfrac{T}{q \cdot S_0}$
Normal Force = N = N_1 + N_2	$C_N = \dfrac{N}{q \cdot S_0}$
Pitching Moment (+ nose up) = $m_{SLCP} = N_1 L_{Riser} - N_2(L_{Tot} - L_{riser})$	$C_{m,SLCP} = \dfrac{m_{SLCP}}{q \cdot S_0 \cdot D_0}$

Static coefficient results

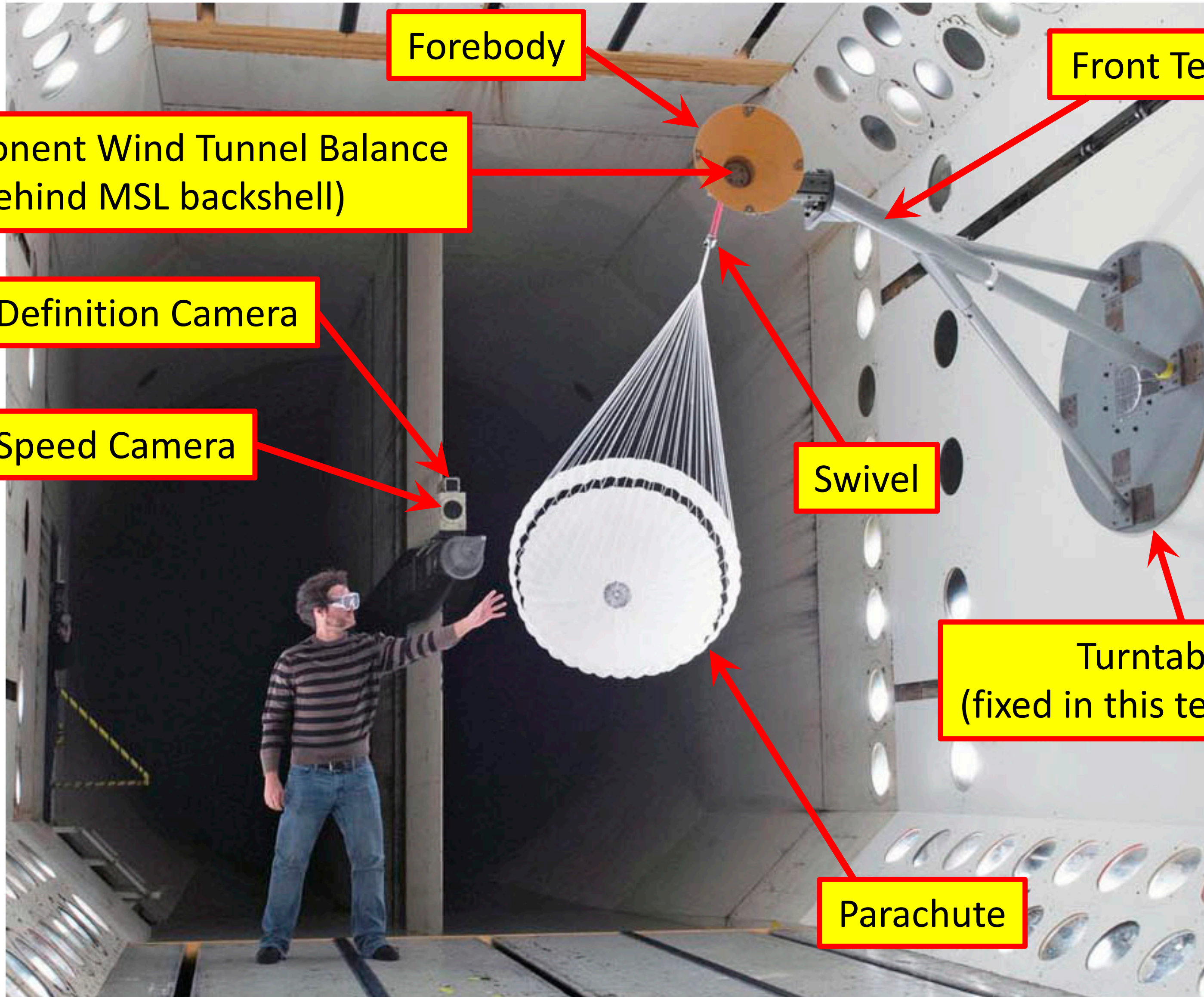
- Parachute w/ Orange Fabric (PIA-C-7020D Type I fabric, “standard” permeability)
- Parachute w/ White Fabric (PIA-C-44378D Type I fabric, low permeability)
- C_m about the suspension lines confluence point



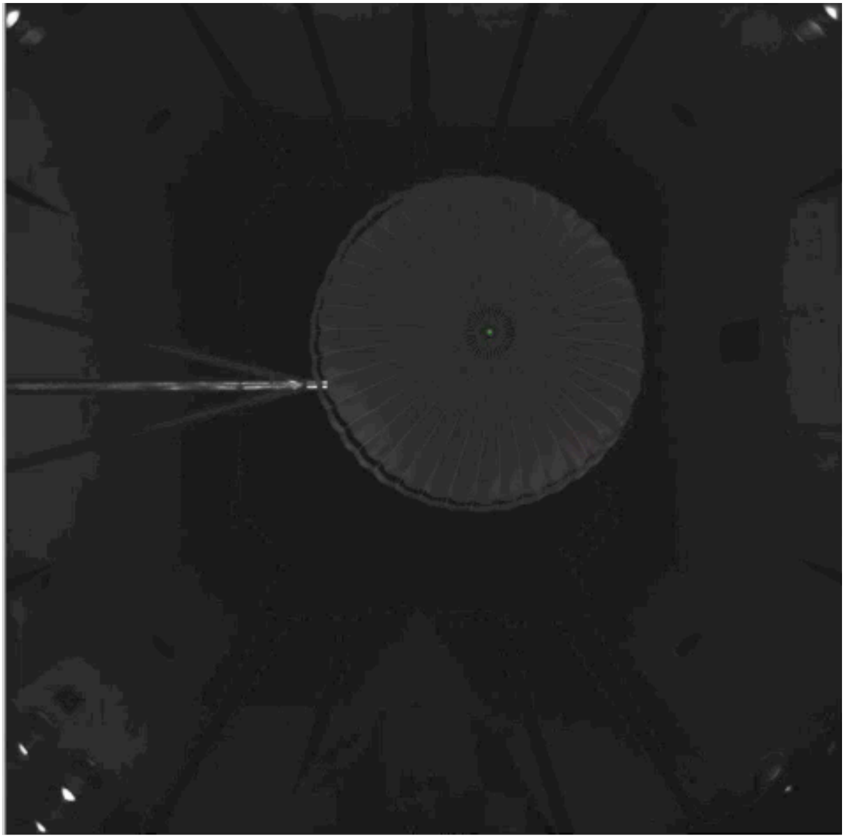


Test setup – drag coefficient & dynamics

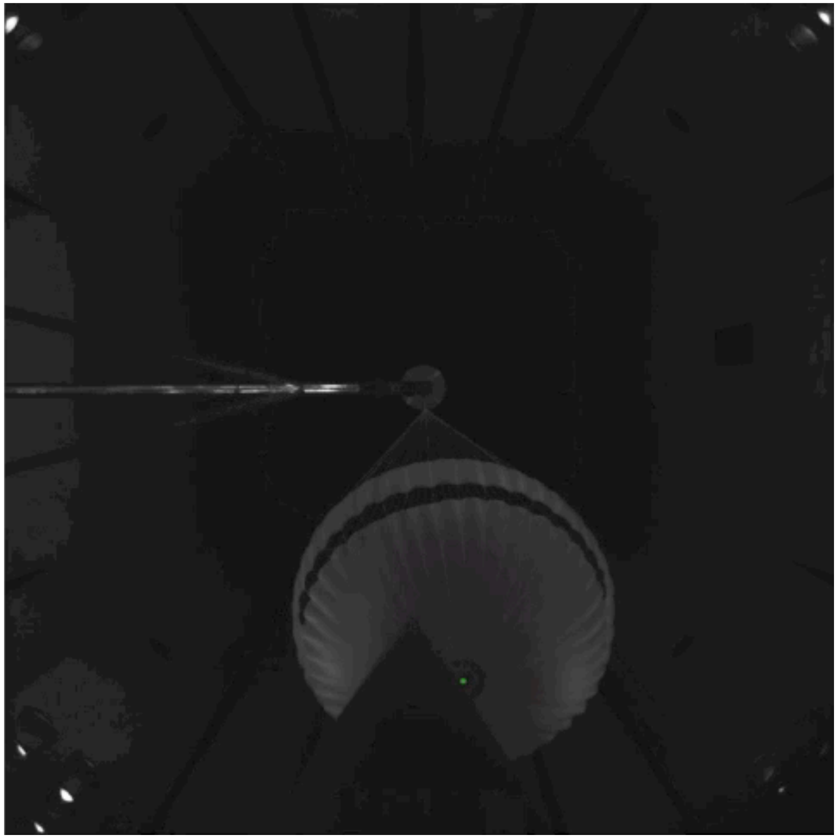
ASPIRE



Recorded 70 s of video with a high speed (HS) photogrammetry camera (120Hz), and tracked the motion of the parachute using a vent tracking algorithm. The parachute force was simultaneously recorded at 600Hz using a 6-component balance.

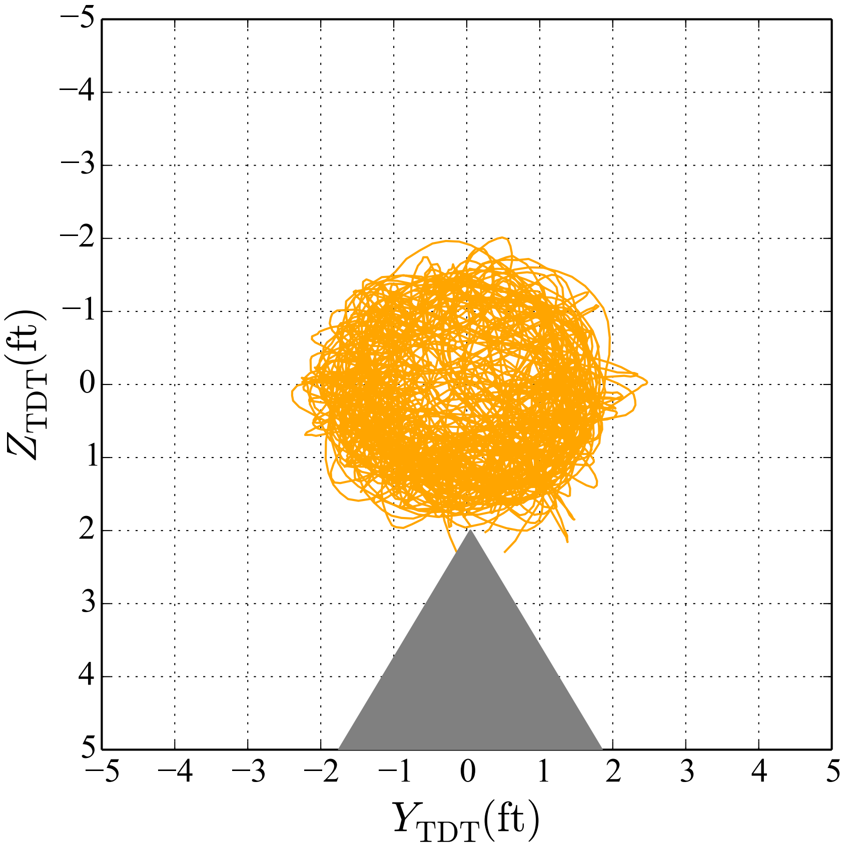


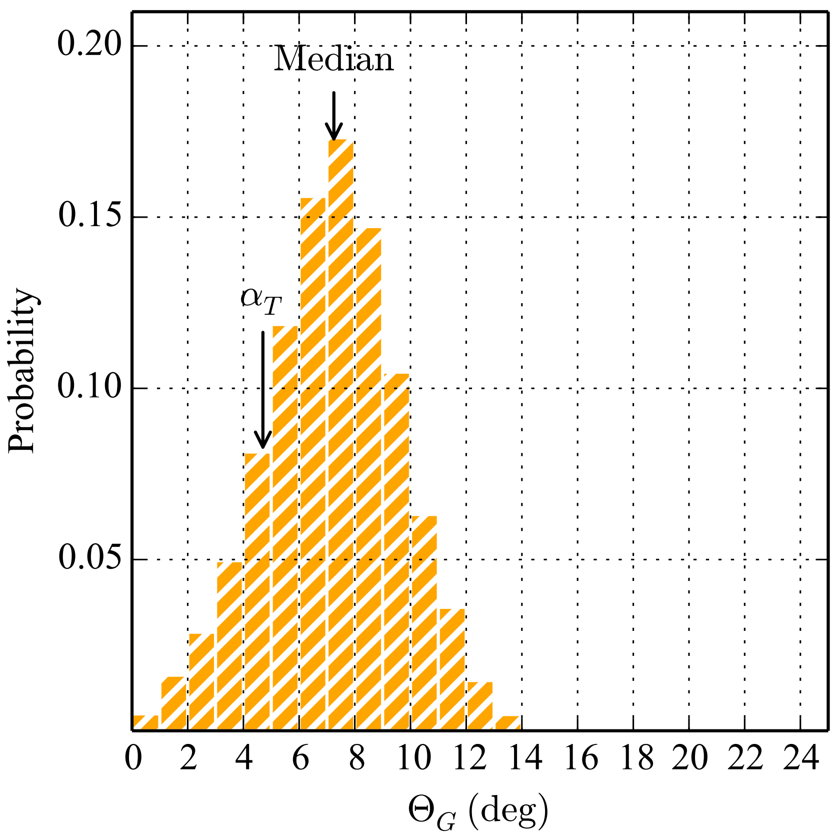
Parachute with “standard” permeability fabric



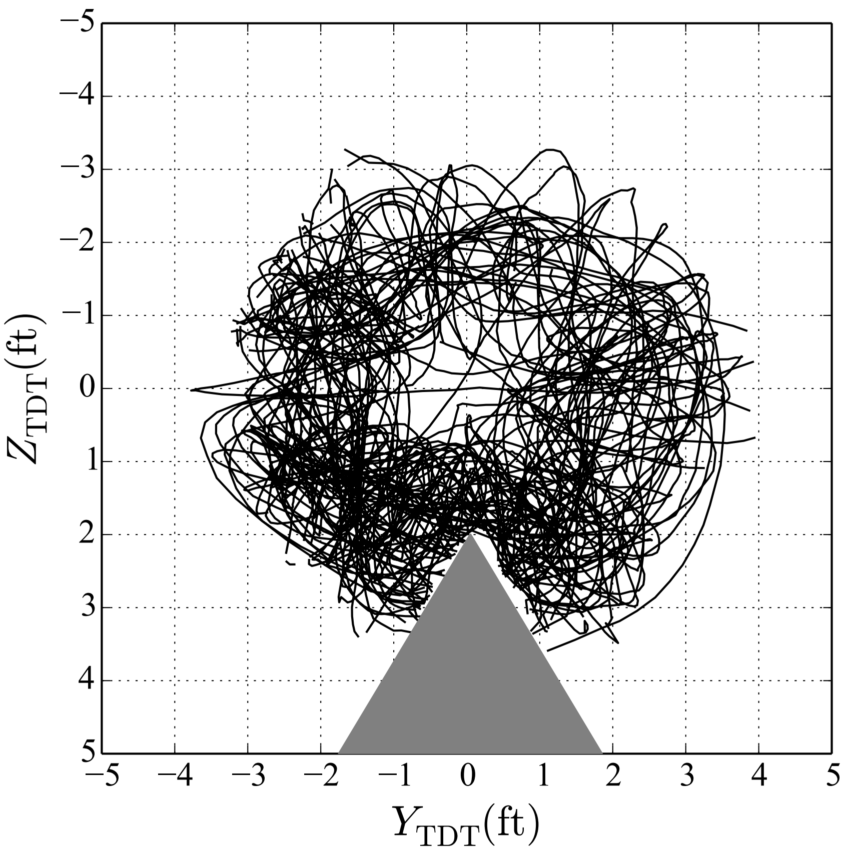
Parachute with “low” permeability fabric

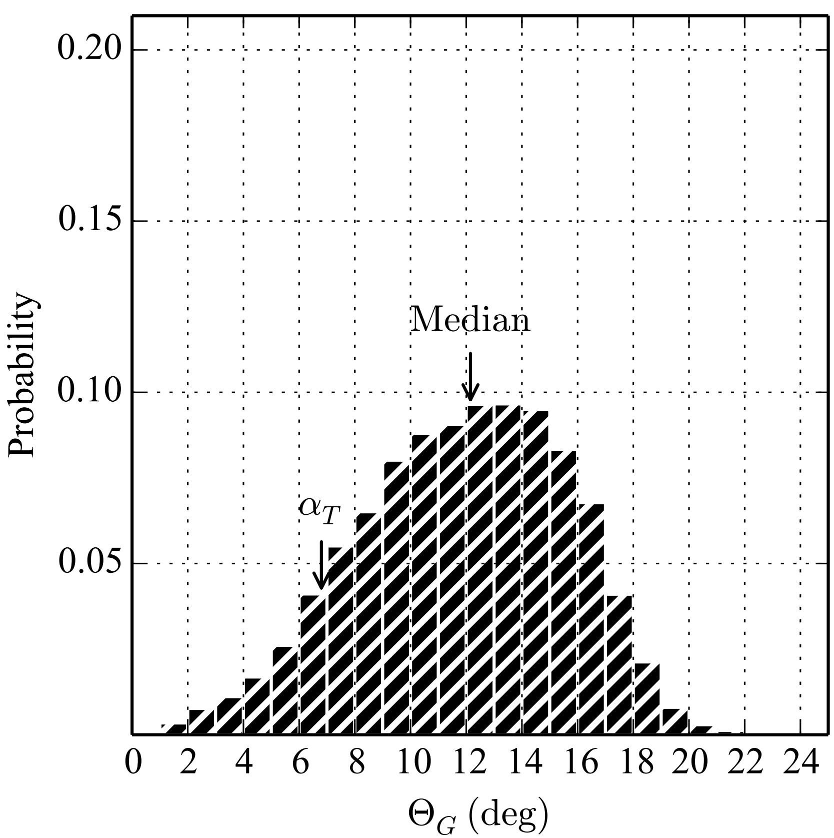
Parachute w/ Orange Fabric (standard permeability)
Test Condition 12, M ~ 0.4





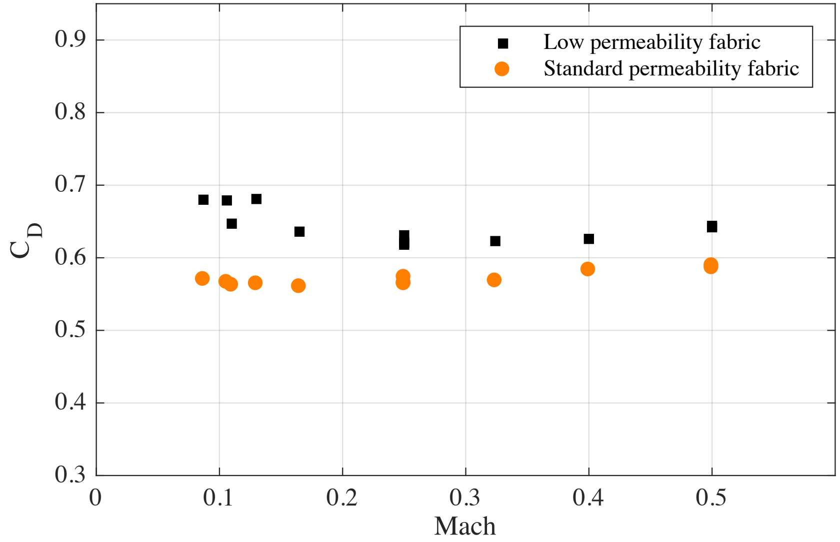
Parachute w/ White Fabric (low permeability)
Test Condition 12, M ~ 0.4





Results – drag coefficient

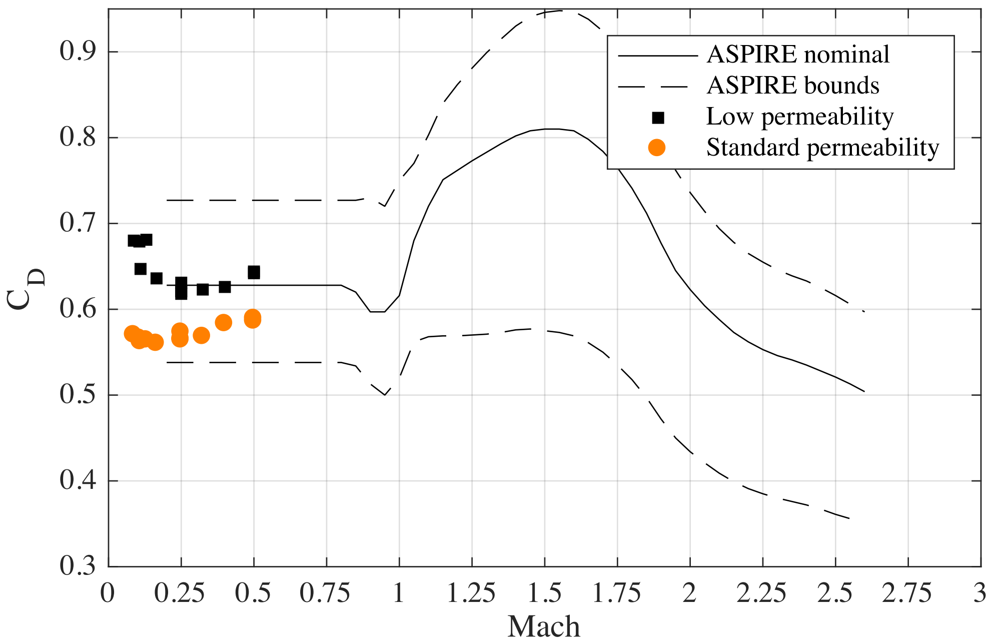
- Simultaneous with parachute motion tracking, measured force exerted by parachute using a six-component balance
- Determined average drag coefficient at several Mach numbers (0.1 to 0.5)



Results – drag coefficient

ASPIRE

- Simultaneous with parachute motion tracking, measured force exerted by parachute using a six-component balance
- Determined average drag coefficient at several Mach numbers (0.1 to 0.5)
- Used existing data to extend these results to supersonic Mach numbers & develop a drag model for ASPIRE

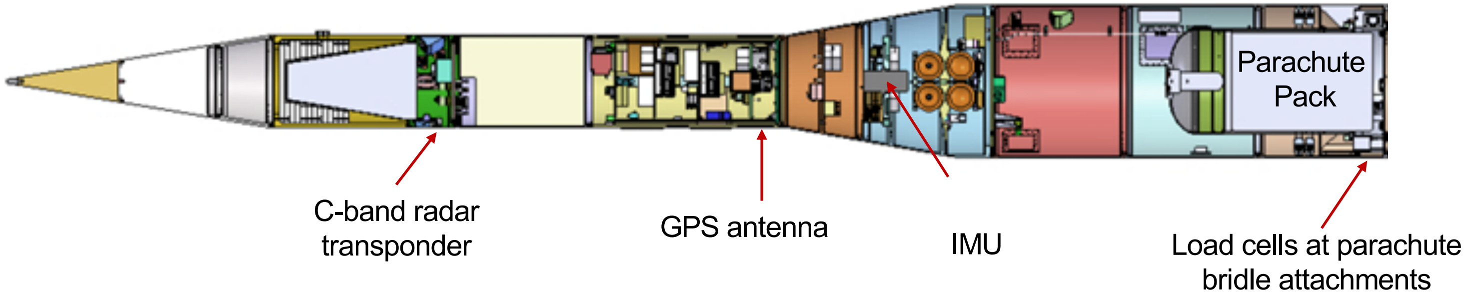


ASPIRE's supersonic flights

- Three successful supersonic flight tests to date:

	Parachute	Load	Test Date
SR01	Build-to-print Mars Science Laboratory parachute	32 klbf	Oct. 4th, 2017
SR02	Strengthened parachute (same geometry stronger materials)	56 klbf	Mar. 27th, 2018
SR03	Strengthened parachute (same geometry stronger materials)	67 klbf	Sep. 7th , 2018

Results: supersonic flights



- ASPIRE payload contained several instruments to

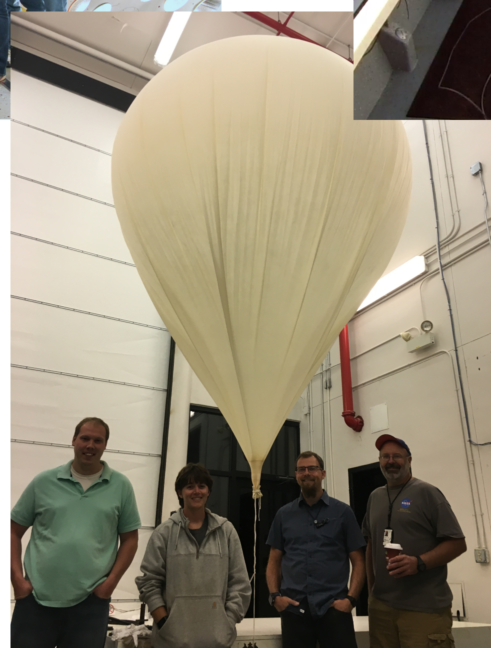
- Allowed reconstruction of

Conclusions & future work

- ASPIRE projected successfully tested two candidate parachutes for the Mars2020 project at low-density, supersonic conditions
- Required developing models for the aerodynamic performance of the parachute
- Models developed using historical data & results from a 2014 wind tunnel test
- Supersonic flight payloads contained instruments to reconstruct parachute performance
- Ongoing work:
  - Reconstruct static aerodynamic coefficients
  - Inform development of parachute models for future tests and for flight at Mars

Acknowledgements

The ASPIRE team at JPL, Langley Research Center, Wallops Flight Facility & Ames Research Center



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Backup

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Test Architecture

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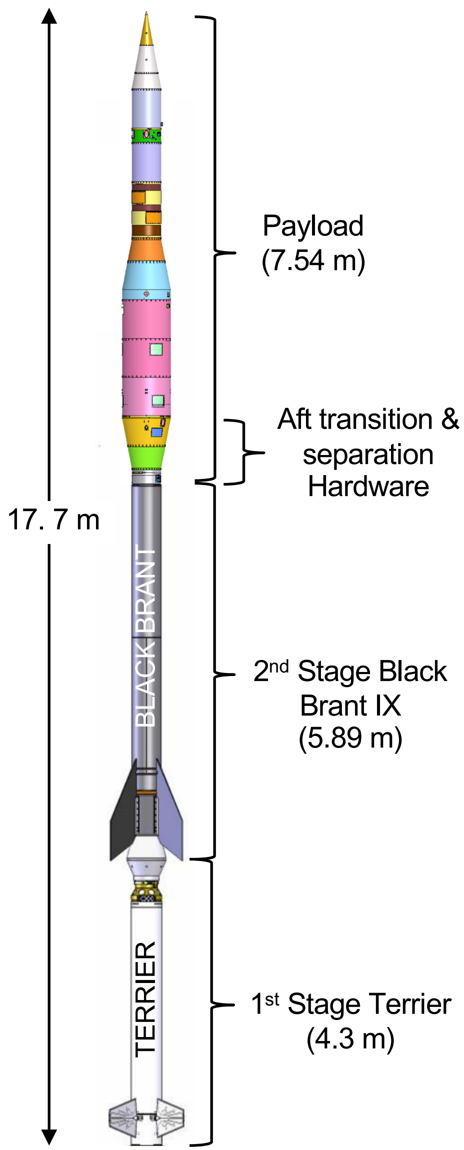
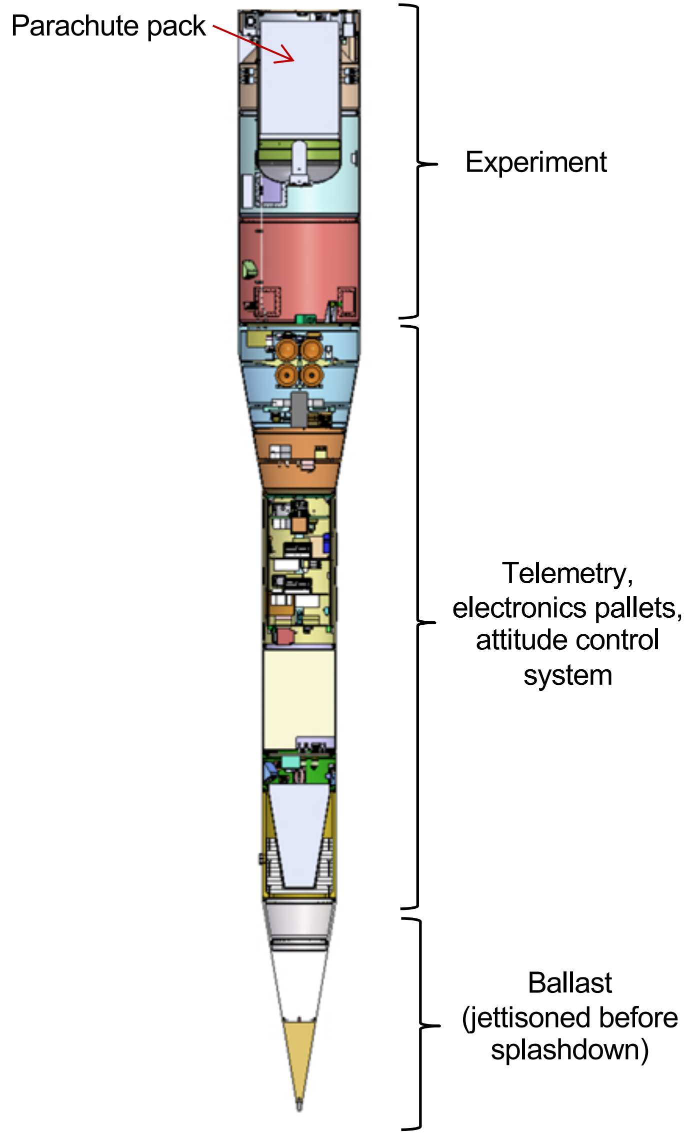
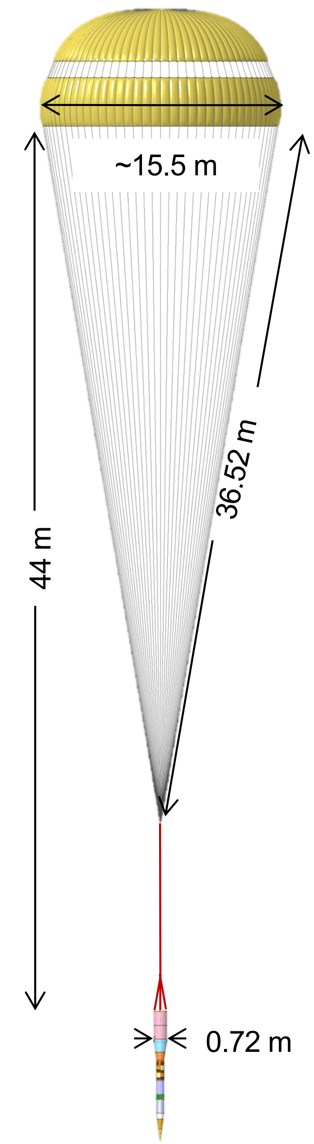
Launch Configuration



Start of Experiment Phase



Parachute Deployed Configuration



Test Architecture

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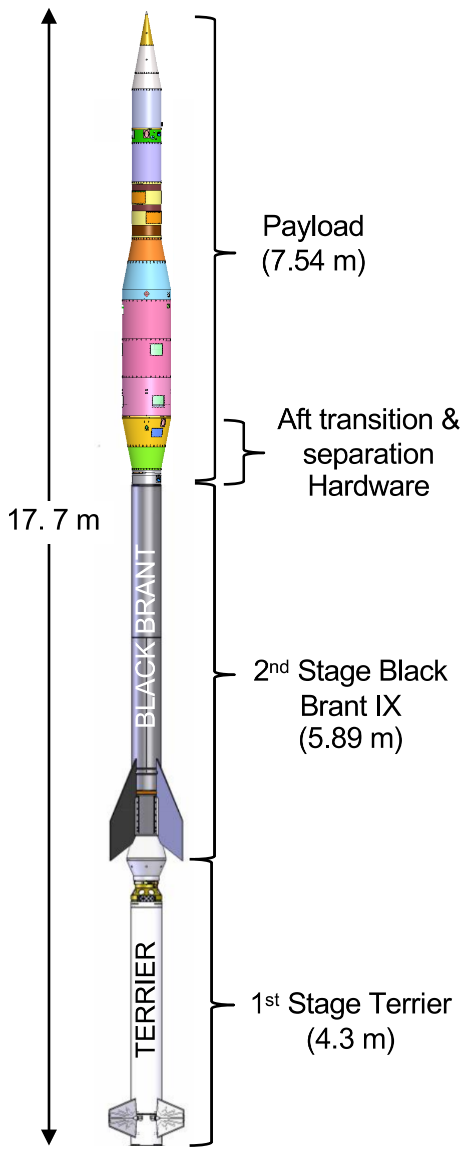

- Rail-launched Terrier Black Brant
- Spin-stabilized at 4 Hz
- Yo-yo de-spin after 2nd stage burnout
- Mortar-deployed full-scale DGB
- Cold gas ACS active from payload separation to before mortar fire
- Recovery aids:
  - Foam provides buoyancy
  - Nosecone ballast (for additional mass & aerodynamic stability) is jettisoned before splashdown
- Payload mass:
  - Launch: 1268 kg
  - Post-separation: 1157 kg
  - Splashdown: 495 kg